

Insulating Biomaterials N01-NS-2-2347

Second Quarterly Progress Report January-March, 2003

National Institutes of Health

National Institute of Neurological Disorders and Stroke

Neural Prosthesis Program



InnerSea Technology

**1 DeAngelo Drive
Bedford, MA 01730**

Contributors:

Dave Edell, PI

Bill Mather, IC Design

Robyn Edell, Testing

Sean Sexton, Instrumentation and Software

Ying-Ping Liu, Assembly and Testing

Karen Gleason, Chem Eng (MIT)

Shannan O'Shaughnessy, Grad Student, Chem Eng (MIT)



Second Quarter Summary

The goal of the Insulating Biomaterials work is to identify and evaluate materials, coatings, and assembly techniques suitable for protection of integrated circuit devices being considered for neural prosthetic applications.

During the second quarter, long term testing continued and samples that failed were analyzed. Implanted telemetry units that failed were removed and analyzed. In addition to the occasional assembly error, devices are failing due to 1) solder flux residues; 2) layered silicone assembly techniques; and 3) failure of silicone encapsulation interface around Teflon insulated interconnect wires.

Solder flux residue failure seems to be linked primarily to the use of a combination of water soluble fluxes and solvent soluble fluxes. Water soluble fluxes are used for surface mount reflow assembly procedures. Solvent soluble fluxes are used for hand soldering. Apparently, there is some interaction between the flux residues, or the flux cleaning procedures that leads to an invisible residual on the surface of the assembled substrates that can form a corrosion pathway.

Layered silicone assembly techniques are often used to ensure complete encapsulation of both sides of a device. However, sometimes the interface between two silicone layers fails and a conductive bridge forms. Why this occurs sometimes, but most of the time does not occur is currently under investigation.

The interface between Teflon insulated interconnect wires and silicone encapsulation has long been an area of concern. However, in initial studies of this, leakage currents from those interfaces were not observed. The initial studies, however, were accomplished using 0.003" platinum wire that was Teflon insulated. Recent failures are with large "hook-up" type wire that is Teflon coated. Because relatively heavy wires are often needed for prototype implants and long term implants that are powered by batteries, this issue is being addressed by identifying a wire insulation that will bond with silicone encapsulation.



An obvious choice of a wire insulation that might be compatible with silicone encapsulants was silicone insulation. Accordingly, two manufacturers of silicone insulated wire were identified and small runs of a multistrand, high flexibility, high flex life, and silver plated copper wire were produced for testing. One surprise was that the wire came coated with either talc or sodium bicarbonate. These coatings are necessary at the point of manufacturing to avoid self-bonding of the wire as it is spooled. However, talc is quite difficult to remove and should not be used for these applications. Sodium bicarbonate should be readily dissolved in water.

When the two batches of silicone insulated hookup wire were cleaned and tested, it became apparent that silicone encapsulants currently in use in our lab did not adhere to the silicone wire insulation. A variety of cleaning techniques, cure conditions, and silicones were attempted in the hope of improving the bonding of the encapsulant to the silicone insulation. Even “adhesive” type silicones did not adhere well to the silicone wire insulation. Adhesion promoters will be explored in an effort to resolve this bonding issue for the silicone on silicone interface.

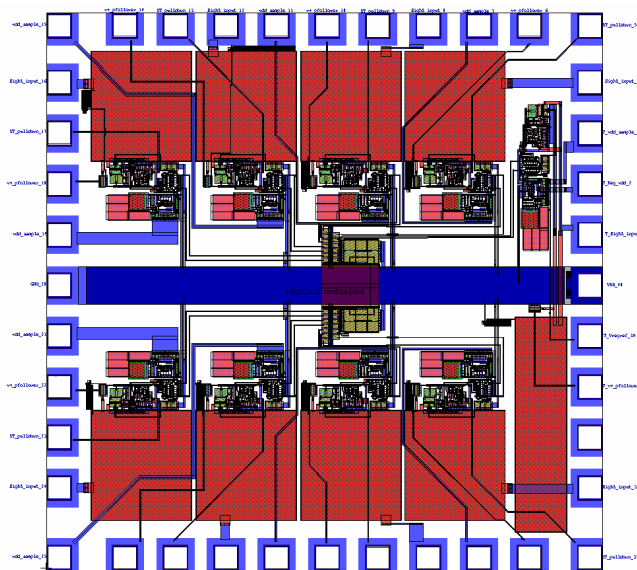


Figure 1: Mask layout composite for PassTest Integrator. Includes 8 free running integrators with self reset, and one diagnostic integrator (on right) for circuit analysis.



PassTest Integrator

There were two versions of the pass test integrator that were developed at Innersea. The purpose of this design was to create a multi-channel integrator that could measure extremely large impedances. Figure 1

The first design had two fatal design errors. One was the use of ESD (electro static discharge) protection diodes where the breakdown voltage was extremely low (tenths of a volt). There was also an error in the current generation on the device that caused only half the chip to be operational. This design was sent away to a laser micro-machine shop to have the ESD diode connections ablated. This was successful in allowing the device to function, but the inputs exhibited an abnormally high leakage current. The excess current was attributed to the laser ablated being marginally conductive. These issues were taken into account and corrected for the next run (PI_021021).

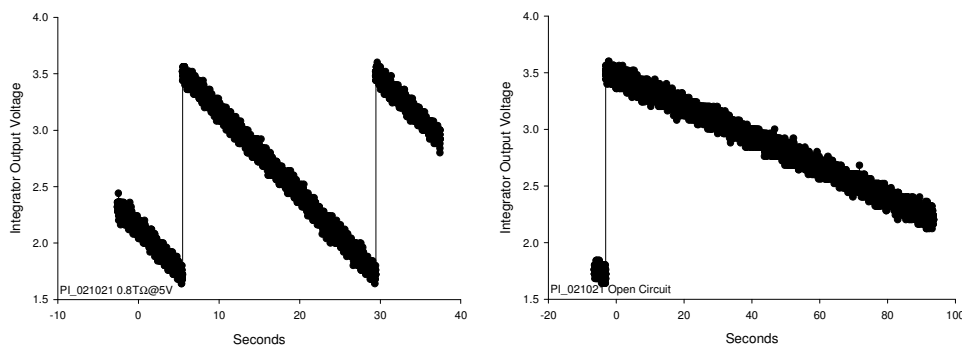


Figure 2: Raw data outputs from integrators with $0.8T\Omega@5V$ input (LEFT) and open circuit (RIGHT) indicating an effective input resistance of a few $T\Omega$.

PI_021021 parts were received at the beginning of 03 and were fully operational (see Figure 2). The only deficiency of the new devices was a higher than expected input leakage current. The magnitude of this current was different for each of the channels on the device but measured on the order of hundreds of femtoamperes. The leakage current was first attributed to three possible causes: 1) ESD diode leakage; 2) Test board leakage; and 3) Package leakage. Test board leakage was tested by pulling the testing pin up out of the board. This



leakage was shown to be a significant but not primary source of leakage. The other sources of leakage were not tested conclusively as yet. This background bias current could be effectively nulled using a variety of techniques. Further evaluation and plans for the new test systems will be developed during third quarter.

CVD Synthesis of New Materials

In previous work, fluorocarbon-organosilicon copolymer thin films were synthesized by hot-filament chemical vapor deposition (HFCVD), and optimization was performed to maximize deposition rate and eliminate metal incorporation from the filament wire. A number of precursors were investigated and the best results were obtained with the combination of 1,3,5-trivinyl-1,3,5-trimethylcyclotrisiloxane (V_3D_3) and perfluorooctane sulfonyl fluoride (PFOSF). In October-March 2003, the focus of the work was on coatings on flat silicon wafers.

Coated silicon wafers were subjected to saline soak testing. Of the six samples analyzed, five samples failed instantly while one sample showed a good resistivity value for a period of several days. Optical microscopy of these samples indicated the presence of several defects in the films.

Several factors were investigated as possible causes for defect formation. These included metal incorporation, flow patterns within the CVD reactor, and the chemistry of film growth. Using a high filament temperature results in films that have a nodular appearance when viewed under atomic force microscopy. This results from a situation where the growth of polymer chains in the gas phase is much more dominant than chain growth on the substrate surface. Once the chains reach a certain length they simply fall out of the gas phase onto the substrate to form nodules. Using a lower filament temperature results in films that have a relatively smooth surface. In this case the polymer chain growth occurs at the surface, providing more uniform growth. This growth chemistry aspect, however, appears to contribute only minimally to defect formation.



The primary source of defect formation appears to be the flow pattern within the CVD reactor. Experiments were performed with two reactors with different flow geometries and these revealed that having a one-dimensional flow helps to reduce the formation of defects. With a multi-dimensional flow, there is a possibility of having recirculation flow areas that generate particles. A more rigorous study is currently underway to confirm this effect.

Appended is a chapter from a book in publication (Murthy, S., D.J. Edell, and K.K. Gleason, *Vapor Deposition of Biopassivation Coatings for Neuroprostheses*, in *Neuroprosthetics: Theory and Practice*, K. Horch and G. Dhillon, Editors. In Publication for 2003.)



CHAPTER 3.3

VAPOR DEPOSITION OF BIOPASSIVATION COATINGS FOR NEUROPROSTHESES

Shashi K. Murthy,¹ David J. Edell,² and Karen K. Gleason³

*Departments of Materials Science and Engineering¹ and Chemical Engineering,³
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, and
Innersea Technology,² One DeAngelo Drive, Bedford, Massachusetts 01730
E-mail: djedell@innersea.com*

Chemical Vapor Deposition (CVD) is a technique by which thin, conformal coatings can be synthesized and applied onto substrates with complex topographies and small overall dimensions. The process does not require any solvents and can be performed in a single step. Polymeric fluorocarbon and organosilicon thin films have been synthesized by two different CVD techniques, plasma-enhanced CVD and hot-filament CVD. Uniform, conformal films are produced on various substrates such as platinum wire, silicon microribbons, and neural probes. The synthesis of fluorocarbon-organosilicon copolymers, which offers the possibility of combining the useful properties of each material type in a single thin film, is also discussed.

1. Introduction

Biopassivation coatings have historically been applied to substrates by spin-on or casting from polymeric solutions. However, coverage of complex three dimensional topography and micron-scale features is difficult with these methods. Thin, conformal coatings cannot be reproducibly made over complex geometries. In addition, the spin-on technique can result in partial alignment of the polymeric chains producing anisotropic properties. For example, in-plane and out-of-plane dielectric constants differ for spin-on polyimide films. Finally, residual solvent may remain in spin-on films. These limitations are especially relevant in the case of neural prostheses, which typically have micron-scale dimensions.

Chemical vapor deposition (CVD) is an alternative to solvent-based application of bulk polymer coatings. This technique is becoming increasingly important as restrictions on biomedical applications by manufacturers of bulk polymers grow. This necessitates the introduction of new materials for biomedical coatings.

There are several advantages of employing CVD. First, CVD provides thin conformal coatings on substrates with complex topographies and small overall dimension. The process does not require any solvents and can be performed in a single step. In addition, the composition of CVD films can be graded with thickness. This allows an optimal layer for adhesion to be deposited first, followed by growth of the composition yielding the best bulk film properties. CVD films are generally amorphous and thus isotropic dielectric properties are expected. Films with low levels of contaminants and impurities can be made via CVD from high purity gaseous precursors. In addition, CVD films contain no residual solvent and CVD processes are compatible with conventional silicon-based integrated circuits processing equipment.

1.1. Plasma enhanced chemical vapor deposition

Plasma-enhanced CVD (PECVD) is a technique that involves the generation of a low density plasma by radio frequency (RF) excitation of a precursor gas at low pressure (< 10 Torr). A schematic diagram of a typical PECVD system is shown in Fig. 1. The plasma consists of ions, radicals and excited neutrals, which can undergo reactions to form a film. Unlike conventional polymers, films made by PECVD do not consist of chains with a regular repeat unit. They are made up of irregular three dimensional cross-linked networks.

A variety of problems have limited the applicability of PECVD films for biopassivation applications. The most significant of these are the high dielectric loss of these films (when compared to conventional polymers), and aging effects upon exposure to the atmosphere.¹⁹ Both of these effects can be



related to the high density of trapped radicals in plasma deposited materials, so-called “dangling bond” defects. When exposed to the atmosphere, these dangling bonds are oxidized, leading to concomitant changes in film structure and properties. Dangling bond defects can originate from electron impact fragmentation of gaseous reactants, UV irradiation,¹⁸ and/or ion bombardment of the surface.²⁰ Plasma exposure of the surface also increases the cross-linking density of the film. Although some cross-linking is desired, an extremely high degree of cross-linking can result in brittle and inflexible films.

These shortcomings can be limited by pulsing the plasma excitation on a millisecond time scale. When the RF power is on, both ions and reactive neutrals are produced in the gas phase. However, ions often have much shorter lifetimes than neutrals. Hence when the RF power is turned off, the ratio of neutrals to ions will increase and film deposition from reactive neutrals will be favored. Also, the decrease in ion bombardment leads to a reduction in the number of dangling bonds and the degree of crosslinking in the growing film.⁹⁻¹¹

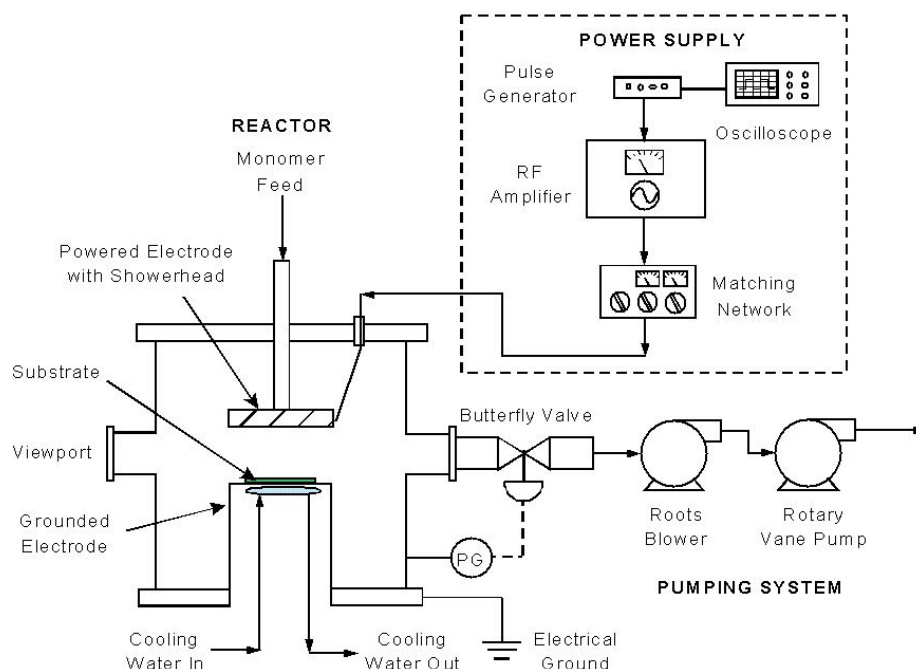


Fig. 1. Schematic of a typical parallel-plate PECVD system.

1.2. Hot-filament chemical vapor deposition

In hot-filament CVD (HFCVD), a precursor gas is thermally decomposed by a resistively heated filament (Fig. 2). The resulting pyrolysis products adsorb onto a substrate maintained at room temperature and react to form a film. This method does not involve ion bombardment or UV irradiation, and has been shown to provide films with a substantially lower density of dangling bonds and crosslinking.¹² Films produced by this method can be characterized more easily because there are fewer reaction pathways and since pyrolysis reactions are well documented in the literature. The temperature range required for pyrolysis depends on the identity of the precursor gas selected.

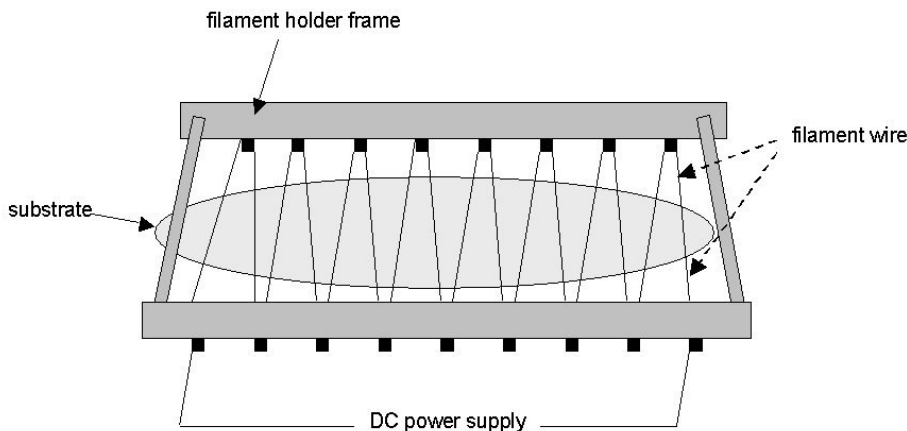


Fig. 2. Schematic diagram of a filament holder used in HFCVD. The holder is mounted on the grounded electrode of the CVD reactor (Fig. 1) and the substrate is placed below it. Precursor breakdown is achieved by resistively heating the filament wire.

2. Fluorocarbon Thin Films

Fluorocarbon polymers are well known for having highly desirable properties for biomedical applications. These properties include chemical stability, electrical insulation, and biocompatibility. One such polymer, poly(tetrafluoroethylene) (PTFE, also known as Teflon®), has been used widely as a biomaterial. Application areas include vascular grafts, heart valve components, sutures and tissue reconstruction, to name only a few. Extensive work has been done on the vapor deposition of fluorocarbon thin films. A comprehensive review of work in this area has been written by d'Agostino et al.⁴ The use of plasma-polymerized fluorocarbons as biomaterials has been discussed by Gombotz and Hoffman.⁶

Limb et al.¹¹ developed a method to deposit fluorocarbon films spectroscopically similar to poly(tetrafluoroethylene) (PTFE) using PECVD. The precursor used in this process was hexafluoropropylene oxide (HFPO). It was demonstrated that the chemical composition and physical properties could be tuned by pulsing the plasma excitation, as shown in Fig. 3.¹¹

The cross-linking density of fluorocarbon films produced by PECVD can be optimized to allow shaping of microribbon cables. Silicon microribbons having a cross-sectional dimension of $100\text{ }\mu\text{m} \times 4.5\text{ }\mu\text{m}$ and 1.5 cm probe shafts have been coated. The pulsed PECVD process must not only conformally coat the shaft while leaving the tips bare but also maintain a configured shape. The microribbon shafts are originally straight and they need to be bent in order to have the fingers oriented in the correct direction. For probes having tip fingers parallel to the shaft a simple 90° bend is needed but for designs where the fingers are perpendicular to the shaft, a 90° bend with a 90° rotation is needed.

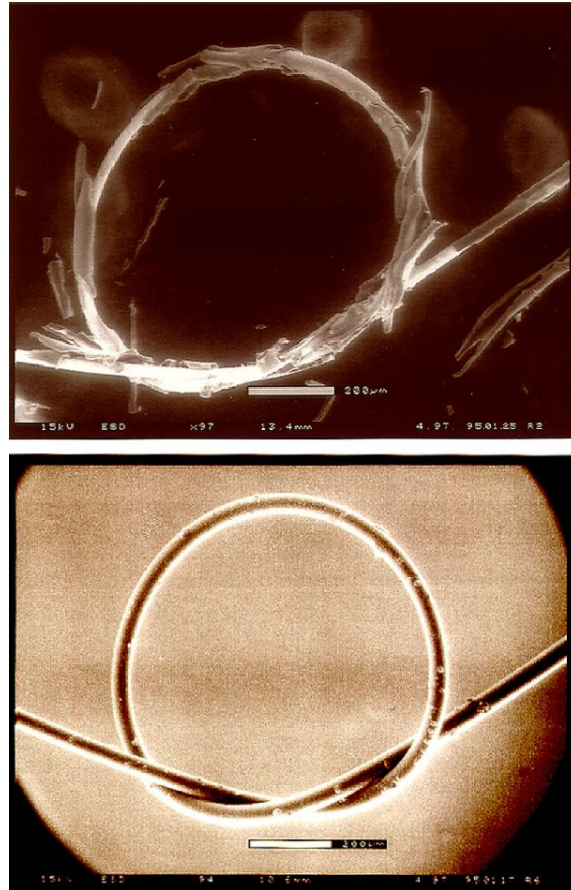


Fig. 3. Comparison of continuous PECVD (top) and pulsed PECVD (bottom) coating of 75 μm diameter wires. In the pulsed PECVD case, the crosslinking density has been reduced below the percolation of rigidity, allowing the structural integrity of the coating to be maintained even after tying the wires into 800 μm diameter loops. Reproduced from Limb et al.¹¹ with permission from the American Institute of Physics.

Figure 4 shows an optical micrograph of a bare microribbon along with coated microribbons having 45° and 90° bends. The two fluorocarbon CVD coated microribbons had a film thickness of 15 μm . The fluorocarbons films maintained the shapes of both bent microribbons and relaxation was not seen for at least a period of 6 months. Furthermore, coated microribbons were soaked in a saline solution at room temperature and no visible relaxation occurred. Cross-sectional views of a coated microribbon are shown in Fig. 5.

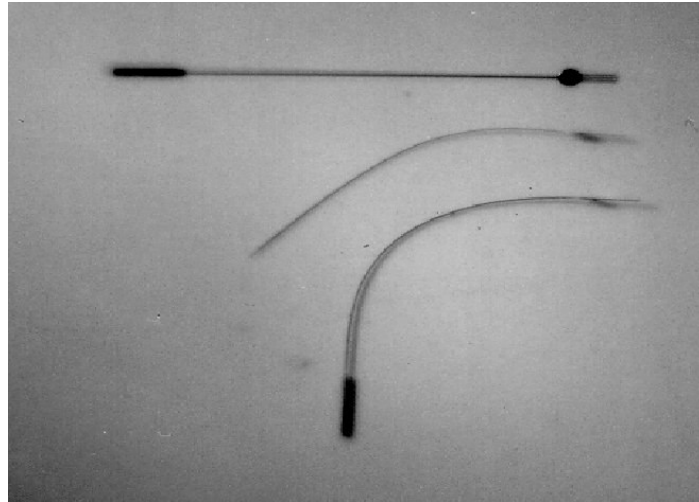


Fig. 4. Shaping of UM microribbon cable via coating with pulsed PECVD fluorocarbon. Optical micrograph of a bare microribbon (top) along with two coated microribbons having 45° (middle) and 90° (bottom) bends.

The PECVD technique has also been used to coat neural probes by Limb et al.¹¹ Figure 6 shows a Huntington Medical Research Institute (HMRI) probe coated with a fluorocarbon film. The coating produced by PECVD is uniform up to the tip (which is 5 μm in diameter).

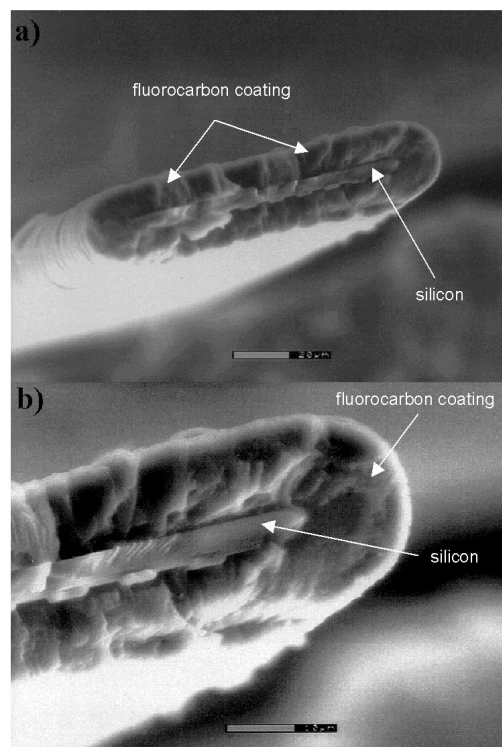


Fig. 5. Cross-sectional view of a CVD fluorocarbon coated silicon microribbon. (a) Full view with scale bar = 20 μm . (b) Corner magnification with scale bar = 10 μm .

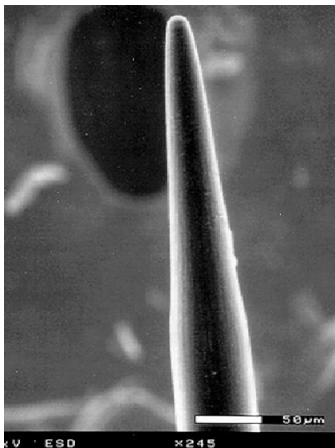


Fig. 6. Environmental scanning electron micrograph of Iridium neural probe with a 9 μm PECVD fluorocarbon coating. Reproduced from Limb et al.¹¹ with permission from the American Institute of Physics.

3. Organosilicon Thin Films

The use of organosilicon films prepared by CVD techniques as biomaterials has been investigated by several researchers. Organosilicon coatings on Celgard®-2400 and Silastic® membranes were deposited from two cyclic silicone precursors (hexamethylcyclotrisiloxane and octamethylcyclotetrasiloxane) using PECVD by Chawla.² Coating the membranes resulted in a lower degree of adhesion of platelets and leucocytes compared to uncoated controls. Ishikawa et al.⁸ examined a number of organosilicon monomers, including D₃, and found that the number of platelets adhering to coated glass slides and the ATP released from these platelets in a human blood *in vitro* system was 10–30% less than the uncoated slides. Hasirci⁷ investigated the deposition of HMDSO on activated charcoal, used in hemoperfusion, by PECVD. It was found that the silicone coating significantly reduced damage from the charcoal granules to platelets, erythrocytes and leucocytes in sheep's blood, without substantially reducing the absorptive capacity of the charcoal. Cannon et al.¹ have described the synthesis of a fine neurological electrode consisting of a 125 μm diameter W-26 at.% Re wire coated with plasma polymerized hexamethyldisilazane.

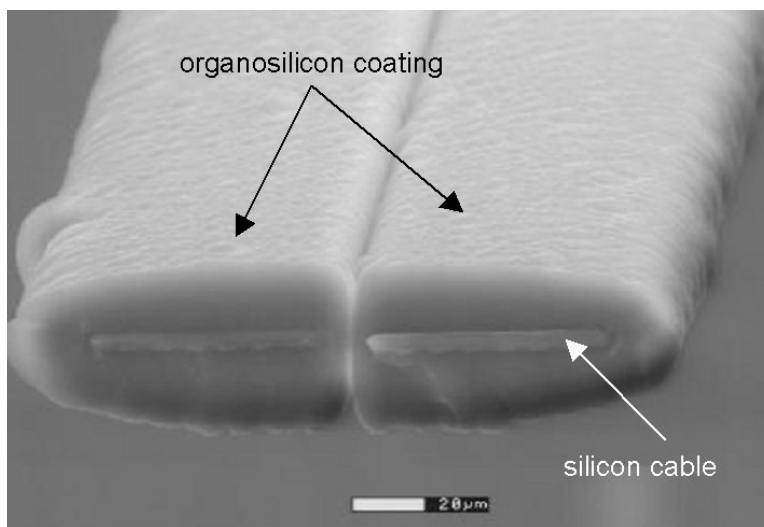




Fig. 7. Pulsed plasma enhanced CVD organosilicon coated silicon microribbon cable. Reprinted with permission from *Chem. Mater.* 2000, 12, 3488. Copyright 2000 American Chemical Society.

Some of the characteristics of silicones are more desirable than those of fluorocarbons for biopassivation applications. Most importantly, the chemical nature of silicones enables covalent bond formation with the native silicon dioxide layer on silicon substrates, creating excellent adhesion. The high strength of a covalently bonded interface is desired for long-term protection of the surface. Figures 7 and 8 show PECVD organosilicon coatings on a silicon microribbon cable and a University of Michigan (UM) neural probe, respectively.

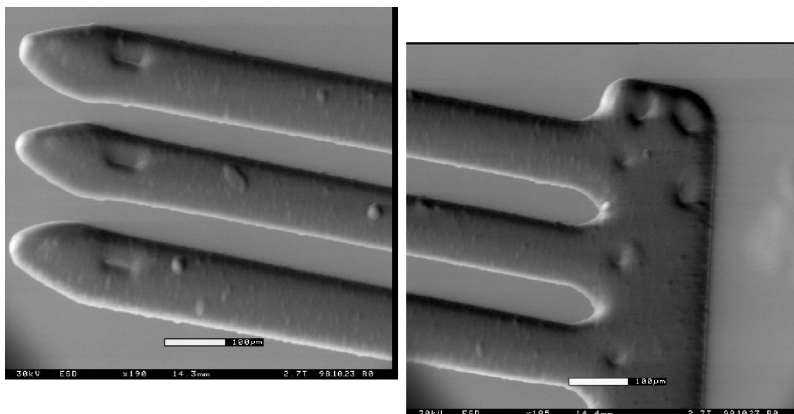


Fig. 8. Pulsed plasma enhanced CVD organosilicon coated UM neural probe.

Reducing the amount of crosslinking in plasma silicone coatings enables the coatings to be more flexible and adhesive under mechanical stress.¹⁷ As in the case of the fluorocarbon films, the continuous plasma process gave brittle coatings, while pulsed PECVD produced more flexible coatings on wires (Fig. 9). The precursor used in this work was hexamethylcyclotrisiloxane (D_3).

Organosilicon films deposited from D_3 using HFCVD had better resolved chemical structures compared to those produced by PECVD, as illustrated in the Fourier transform infrared (FTIR) spectra in Fig. 10.¹⁶ Further, atomic force microscopy (AFM) showed that these films were very smooth in comparison to fluorocarbon films deposited by HFCVD (Fig. 11). This characteristic of silicones may be useful in prostheses where a low surface roughness is required to minimize tissue damage.

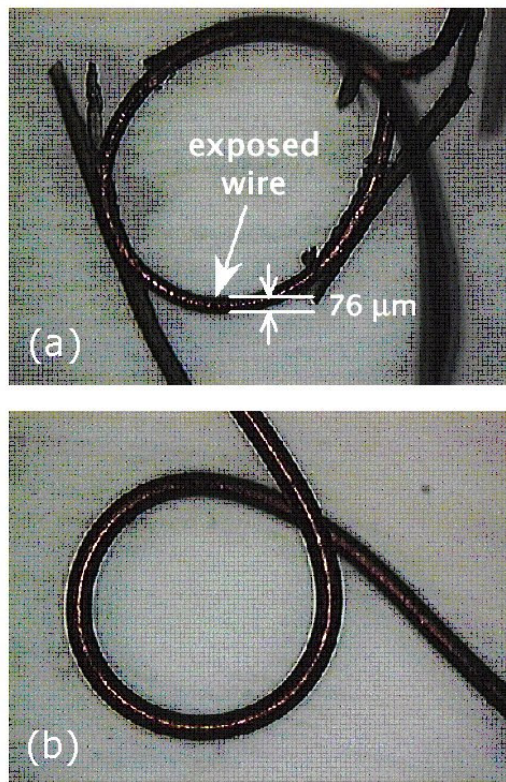


Fig. 9. Optical micrographs of silicone coated test wires tied into 750 μm loops. The continuous PECVD coating (a) delaminated, while the pulsed PECVD coating (b) showed excellent adhesion and flexibility. Reprinted with permission from *Chem. Mater.* 2000, 12, 3488. Copyright 2000 American Chemical Society.

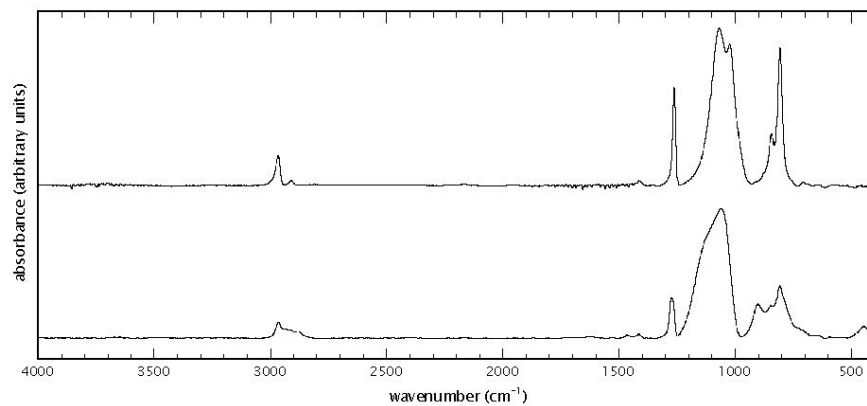


Fig. 10. FTIR spectra of PECVD organosilicon film (bottom) and HFCVD organosilicon film (top) deposited from D_3 .¹⁶ The HFCVD film has fewer and narrower bands, indicating a better resolved chemical structure. Reproduced by permission of The Electrochemical Society, Inc.

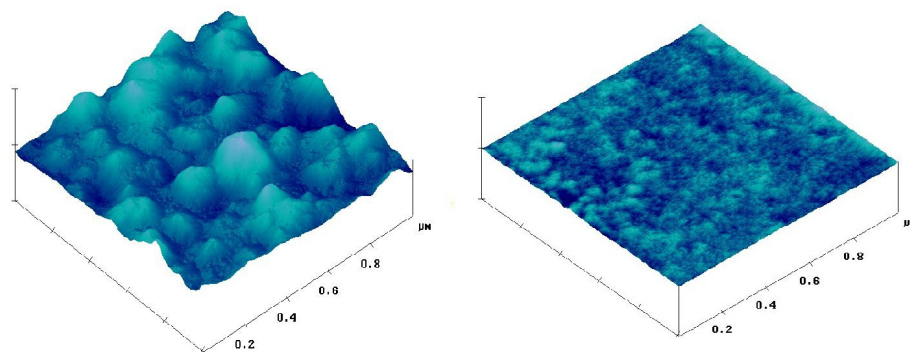


Fig. 11. Atomic force micrographs of HFCVD fluorocarbon film (left) and HFCVD organosilicon film (right). The vertical scale for both images is 75 nm/div and the area covered is $1\mu\text{m}^2$.

Organosilicon coatings were deposited onto 50 μm diameter platinum wires by HFCVD from D_3 at various filament temperatures. These experiments showed that higher filament temperatures produced extremely brittle coatings while lower temperatures produced flexible, conformal coatings (Fig. 12). This difference was attributed to the higher degree of cross-linking observed at higher filament temperatures, analogous to the continuous-wave PECVD coatings described earlier.

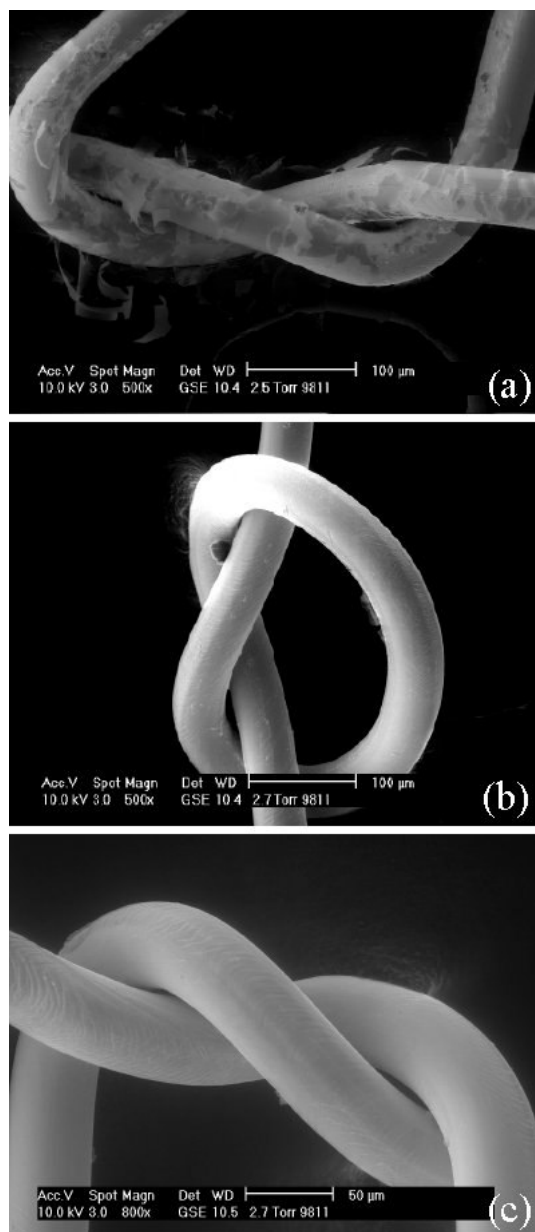


Fig. 12. Organosilicon wire coatings deposited filament temperatures of (a) 1100 °C, (b) 1000 °C, and (c) 860 °C. Lower filament temperatures produce less brittle coatings.

4. Fluorocarbon-Organosilicon Copolymers

When considered separately, fluorocarbon and organosilicon polymers have several properties that are attractive for biopassivation applications. Fluorocarbon polymers have low dielectric constants, high resistivities, low surface energies and high hydrophobicity. However fluorocarbon coatings have a high degree of surface roughness and their adhesion to silicon substrates is poor. Organosilicon polymers, on the other hand, adhere very well to silicon substrates and are smooth (low surface roughness). However the electrical properties of organosilicon polymers such as dielectric constant and resistivity are not as



attractive as those of fluorocarbons. A fluorocarbon-organosilicon copolymer therefore has the potential to incorporate the desirable attributes of each class of material into a single coating.

An important advantage of CVD is the ability to create copolymers that are difficult to synthesize by bulk or solution techniques, such as fluorocarbon-organosilicon copolymers. Organosilicon polymers having fluorocarbon pendant groups of the form $\text{CH}_2\text{CH}_2(\text{CF}_2)_x\text{CF}_3$ as well as polymers having short fluorocarbon segments attached to siloxane chains have been synthesized by solution chemistry techniques.^{3,5,14,15} CVD offers an easier route to make these polymers as the process does not involve a solvent and can be performed in a single step.

Fluorocarbon-organosilicon copolymer thin films have been synthesized by HFCVD from hexamethylcyclotrisiloxane and hexafluoropropylene oxide.¹³ Covalent bonding between the fluorocarbon and organosilicon moieties in the films was verified by Fourier transform infrared spectroscopy and nuclear magnetic resonance spectroscopy. Future work in this area will include studies of physical, chemical and electrical properties of this copolymer material to determine its feasibility as an insulating coating for neuroprostheses.

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